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Modem Characterization Through a Wideband, Hard-Limited Ka-Band Satellite Channel

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Abstract
NASA is using a commercial customized TDMA/FDMA bandwidth on demand modem for use with the Advanced Communications Technology Satellite (ACTS) to highlight the numerous services and experiments that can be performed using small Ka-Band terminals. Characterizing the modems proved challenging due to the characteristics of the satellite transponder. The ACTS channel is hard-limited and up to 900 MHz wide. The channel has some unusual dynamic properties due to the satellite and antenna system, which make modem testing through the satellite challenging and the test requirements stringent. The satellite Multi-Beam Antenna (MBA) has a 1 hertz oscillation induced by the momentum wheel, which causes the transmit antenna pattern to move slightly. This results in a 1 hertz oscillation in the ground station receive power, with amplitude changes up to 1 dB depending on terminal location within a spot beam and associated gain slope. In addition, ACTS experiences a solar induced "thermal event" each day. This "thermal event" occurs when the sun heats the antenna support structure causing the transmit and receive reflectors to mispoint. This results in a slowly decreasing or increasing power density at the ground station receiver as the antenna pattern moves off bore-site.

This paper describes the method used to fully characterize the TDMA/FDMA modem through the ACTS wideband, hard-limited transponder. In particular, techniques are discussed for conducting RF measurements on such a channel, the affect that the thermal characteristics and 1 hertz variations have on the accuracy of the results, and suggested means to minimize the error and provide useful and valuable data.

Introduction/ACTS Characteristics

The ACTS Satellite was launched in September 1993 to demonstrate advanced technologies for communication satellites. The main technologies were multi-beam antenna systems (including small spot beams), on-board baseband processing, high speed IF switch matrix, wideband transponders, and the use of Ka-band frequencies (30 GHz uplink, 20 GHz downlink).

ACTS antenna beams cover approximately one-third of the continental United States using small high gain spot beams. Each beam is approximately 100 miles in diameter having a .3° beamwidth. The small beams concentrate the energy to and from the satellite antenna over a small area allowing ground stations with smaller antennas to transmit/receive higher data rates. Small high gain beams require stringent pointing requirements and stability. Disturbances to spacecraft antenna pointing caused by orbital effects and thermal distortions can effect the signal and link measurements.

The antenna system on the ACTS satellite experiences several types of thermal distortions.[1] The primary thermal distortions of concern to the modem characterization measurements are the fast varying events and the diurnal variation. Figure 1 illustrates a typical downlink power signature from ACTS in the Cleveland fixed beam (without compensation). The diurnal event lasts throughout the day while the fast varying event in the figure occurs between 1900-2100. The fast varying events are caused by sun illumination of the sub-reflector causing the antenna to mispoint. The time and duration of the fast varying events are known. Although applications and experiments can operate seamlessly during these periods, precise RF measurements are not made during these times. The diurnal variation is a slow moving event possibly caused by the thermal distortion of the antenna support system. Although applications and experiments can operate throughout the day, adjusting the transmit reflector to compensate for the thermal distortion minimizes the pointing loss for more detailed measurements. However, even with compensation the event must be well understood and considered when making precise link measurement.

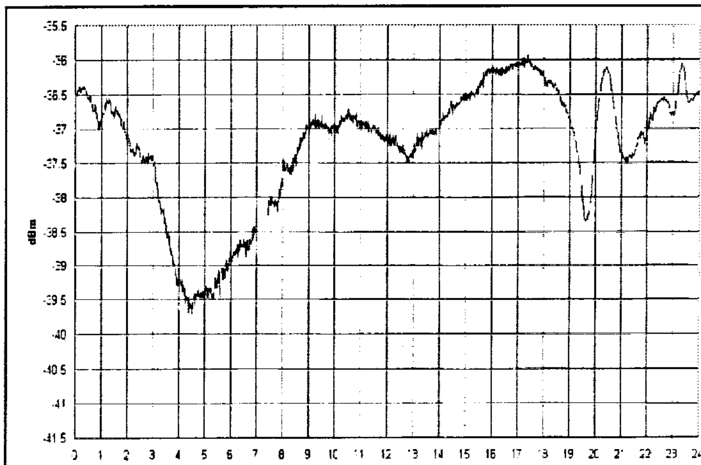

Figure 1 – Diurnal Variation and Fast Varying Thermal "Events".

Non-thermal distortions must also be considered. Of particular interest on ACTS is a 1 Hz sinusoidal oscillation of the downlink power. Experiments to characterize this phenomenon indicated as little as .1 dB variation at beam center (measured) and as much as 3 dB at beam edge (theory) depending on time of day and antenna beam gain slope. Measured data resulted in 1 dB peak variation.

Figure 2 and Figure 3 illustrate typical channel characteristics experienced during the modem characterization experiment. Figure 2 is a time elapsed spectral plot of the received signal. The amplitude variation is approximately .8 dB peak-to-peak. The cause of the oscillation was attributed to the resonant frequency of the main reflector excited by the operation of the momentum wheel pitch control loop. All beams experience the variation, however the amplitude of the variation is a function of the beam slope, which may be very large due to the high gain Ka-Band spot beams. Combined with the thermal distortions, the amplitude of the 1 Hz variation varies throughout the day. Typical amplitudes were .2 to .6 dB, with maximum amplitude variation up to 1.0 dB.

Figure 3 illustrates the change in signal level over the course of several minutes. The receive power increased approximately 1.5 dB over 1000 seconds. Thus, if the signal level and E_b/N_o were recorded only at the beginning of the test period, the BER would improve throughout the test, distorting the data. Consequently, if the power (and associated E_b/N_o) reduced throughout the test, the measurement would also be distorted since a large number of errors would occur as the link degraded. The final BER would be dominated by the errors in the low E_b/N_o, yet the measurement would reflect a high E_b/N_o, thus recorded incorrectly.

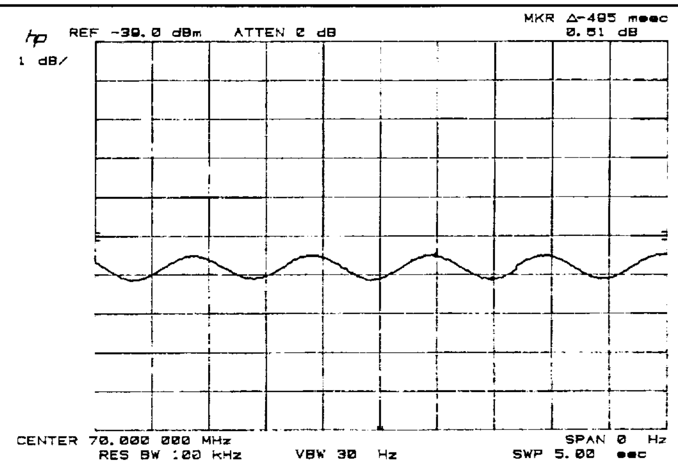

Figure 2 – One Hertz Oscillation.

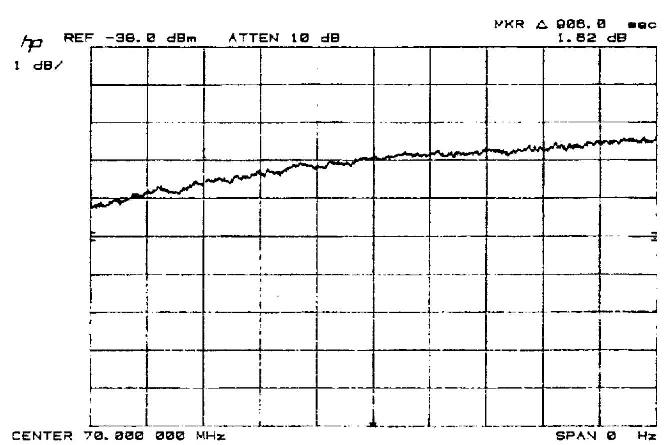

Figure 3 – Receive Power versus Elapsed Time.

ACTS Microwave Switch Matrix

The two operational modes of the satellite are the baseband processor and the IF Switch Matrix. The baseband processor works in a time division multiple access (TDMA) system with a fleet of very small aperture terminals (VSAT's) using 1.2m parabolic reflectors and the hopping spot beam MBA system. The baseband processor demodulates incoming data, identifies how to route the data to the destination ground station then re-modulates the data and transmits the packets to the appropriate ground station in the appropriate beam.

The microwave switch matrix mode uses a four-by-four matrix switch to route the uplink antennas to the appropriate downlink antennas in a "bent-pipe" repeater fashion. Each port of the matrix switch output to one of the four-wideband transponders, each over 900 MHz wide with approximately 800 MHz of useable bandwidth. Each transponder frequency response is nominally flat with less than 1 dB peak-to-peak ripple. Each transponder can connect to any of the antennas in the MBA system using a waveguide switching system.

The microwave switch matrix mode or MSM mode is a flexible configuration for experimenters using the ACTS system. Although the "bent-pipe" mode of satellite operations existed before the advent of Ka-Band, the technologies made possible by Ka-Band make the MSM mode capable of carrying traffic from 4.8 kbps up to 622 Mbps depending on the ground station configuration. Uses of the MSM mode include the Ultra Small Aperture Terminal (USAT) and High Data Rate (HDR) ground station experiments. The USAT's conduct low (4.8 kpbs) to moderate (8 Mbps) rate experiment applications using .6m antennas and HDR stations use the MSM for high rate (155 Mbps and 622 Mbps) data transfers and network experiments using 3.4m antennas. Other experimenters have developed custom terminals for use with the MSM mode using a variety of moderate data rates.

Besides application experiments, the flexibility of the MSM mode also allows technical experiments for characterizing the wideband transponders, different modulation techniques and modems, Ka-Band components (low noise amplifiers, transmit amplifiers, etc), spacecraft analysis (1 Hz oscillation), propagation analysis (wet antenna studies, diversity experiments) and more. All these characterization experiments rely on a well-understood and reliable satellite channel for accurate measurements. In addition to the thermal events described, the ACTS transponders are hard limiting channels, which further adds to the challenge.

Hard Limiting Channel Characteristics

Hard limiting amplifiers are often used in communication channels to remove amplitude variations in the signal or present a constant power level to an amplifier with a precise operating level to improve efficiency. Because hard limiting amplifiers are non-linear devices, intermodulation products (unwanted products derived from the sum of integer multiples of the input signals) and signal suppression occurs.

Each transponder of ACTS contains three hard limiting amplifiers. The first amplifier is located prior to the IF switch matrix. These amplifiers maintain a similar and constant power level to each port of the switch matrix to minimize small signal suppression caused by larger signals occurring in the IF switch matrix simultaneously. Because ACTS could support both high rate (high power) HDR experiments through one channel and a low rate (low power) USAT experiment through a different channel simultaneously, cross-talk between switch ports could result in signal suppression of the USAT signal.

The second hard limiting amplifier occurs prior to the traveling wave tube amplifier (TWTA), after the IF switch matrix. These amplifiers maintain constant drive level to the TWTA's for constant satellite downlink power. The hard limiting amplifiers will limit on noise power; that is, the output power of the limiting amplifier is constant with and without a signal present. The final hard limiting (approximate) amplifier is the saturated TWTA. Because the drive is held constant with and without a signal present, the TWTA outputs a constant saturated power level. The noise power output from the TWTA will vary depending on the presence of a signal. A strong signal in the hard limiting channel will suppress the noise and the amplifier will limit the level of the strong signal. If a small signal is present, the noise will suppress the small signal and the amplifier will limit the noise power. In either case, the effective radiated power from the satellite remains constant.

Due to their non-linear characteristics, hard limiting amplifiers affect modulated signals passing through the satellite distorting their signal. The hard limiting amplifiers cause spectral restoration, produces effects such as I-to-Q crosstalk, and causes amplitude and phase modulation (AM-AM and AM-PM conversion), degrading signal quality. The signal degradation occurs because of the amplitude variations of the modulated signal. For constant envelope modulated signals, these degradations are minimized or eliminated.[2] Thus, modulation schemes such as continuous phase frequency shift keying (CPFSK) and minimum shift keying (MSK) are desirable for hard-limited systems.

Filtering is generally performed to limit the bandwidth of modulation schemes such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and offset quadrature phase shift keying (O-QPSK). Filtering these modulation schemes creates amplitude variations causing degraded performance in hard limiting channels.

Both the ACTS baseband processor system (27.5/110 Mbps) and the Link Evaluation Terminal (220/110 Mbps) modems use MSK modulation. O-BPSK and O-QPSK are used in the ACTS High-Data-Rate (HDR) modems to reduce the amplitude variations compared to BPSK and QPSK. Higher order modulation schemes such as 8-PSK are not used due to spectral re-growth and phase changes caused by the ACTS MSM channel. An example of the spectral re-growth can be found at http://mrpink.grc.nasa.gov/grdstns.html (as of August 1999).

BPSK and QPSK are used in the various commercial modems used with the USAT ground stations. Experiments with the HDR ground stations indicated that spectral distortion is a function of the ratio of signal bandwidth to transponder bandwidth. The higher the ratio the greater the distortion.[3] Since the USAT is a low rate, narrow band system, minimal signal distortion is experienced.

Hard Limiting Channel Measurement Techniques

As mentioned earlier, the total power from the satellite is constant due to the hard limiting amplifier limiting on noise and saturating the TWTA. However, the downlink noise power from the satellite varies depending on the signal strength of the uplink signal. The amplifier will hard limit on the stronger of the two signals while the weaker signal experiences suppression. The noise power must be measured accurately for E_b/N_o versus bit error rate (BER) characterizations.

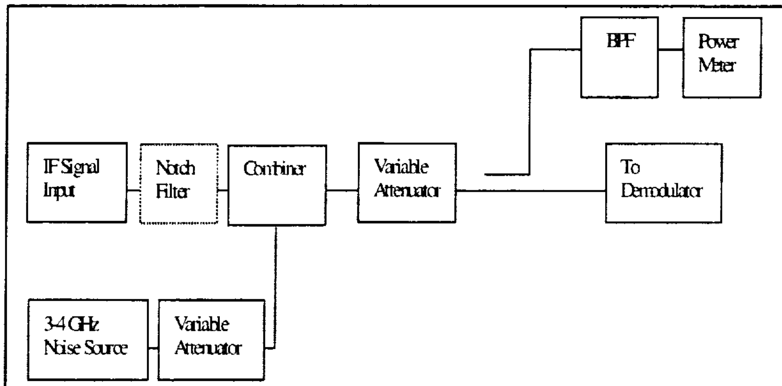

Figure 4 – Signal and Noise Power Measurement System.

The pre-launch testing of the ACTS satellite included a number of characterization experiments to measure bit error rate (BER) and corresponding E_b/N_o. The measurement of signal level and noise power was accomplished using the test system illustrated in Figure 4. Using an automated software control program a power meter was used to measure both the signal power and noise power presented to the demodulator. The control program would provide a calibrated tone (from within the ground system test equipment) to measure signal power and then remove the tone to measure noise power. A calculation of E_b/N_o was derived from the signal and noise power. In tests using only the ground system test equipment, the measurement system derived the proper signal level, noise power and corresponding E_b/N_o.

When used with the ACTS satellite, the noise power presented to the demodulator was saturated in the absence of an uplink signal. During a noise measurement the noise floor from the satellite was higher than that seen by the demodulator during a BER measurement. During a BER measurement, the modulated signal from the modem would suppress the noise floor based on its uplink power. Measuring the noise power without a signal present yielded a false reading.

Two methods were developed to measure the signal and noise characteristics of the communication channel. These methods were used to suppress the hard limited noise floor to an approximate level equal to that under BER measurement conditions. A third method was later developed to account for the on-orbit characteristics.

The first method used a continuous tone at the modulated carrier frequency with like uplink power to suppress the noise floor, as the modulated signal would do during a BER measurement. A notch filter was used to remove the tone from the noise power measurement. A calibrated adjustment was then made to the noise power reading to account for the noise power lost due to the notch filter. Thus by using an in-band tone the existing test system could accurately measure the noise power from the satellite and determine the appropriate noise power density under BER measurement conditions.

The second method used an out-of-band tone to suppress the noise floor. The frequency of the tone was set out-of-band so that the notch filter was not needed. The tone would suppress the noise floor to the same level as the modulated signal would during a BER measurement. The out-of-band tone was located outside the noise power filter bandwidth so that it would have a negligible affect on the noise power measurement—typically several hundred MHz away from the modulated carrier frequency with similar uplink power.

A third method was used to consider the time-varying characteristics of the ACTS communication channel. A spectrum analyzer was used to measure the signal level and noise power density. Two techniques were used to minimize measurement error. The first technique recorded the minimum and maximum signal and noise level. These provided a minimum and maximum carrier-to-noise density ratio, C/N_o, and corresponding E_b/N_o. The second technique used the video averaging feature of the spectrum analyzer to time average the 1 Hz oscillations. Typically 100 averages were used over several seconds for each carrier and noise power measurement.

QPSK Modem Test Results

The system was configured for the modem characterization test using a USAT ground station with a one-watt transmitter with a 1.2m antenna. This provided sufficient uplink power for the experiment with a maximum C/N_o of about 79 dBm-Hz for 5 Mbps (channel rate). ACTS was configured for a loopback connection through the MSM. BER was measured using an internal BER test utility.

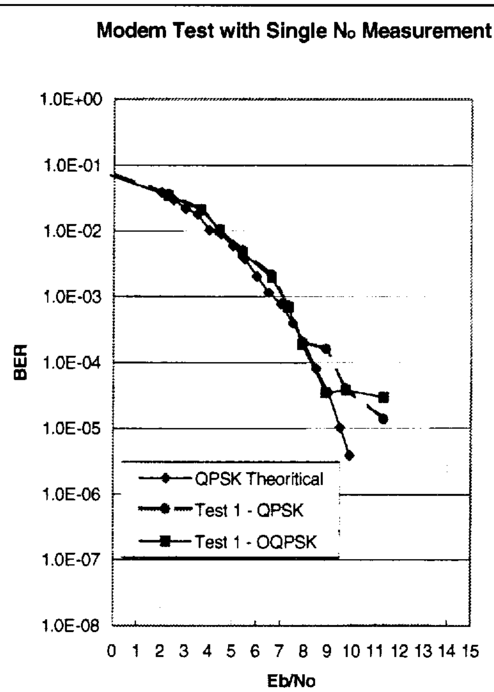

Figure 5 – BER Results, Test 1.

Figure 5 shows two erroneous BER curves for the modem running in continuous mode without coding. The curves are for QPSK and O-QPSK. Performance of QPSK and OQPSK were similar as expected with narrow band signals. These curves show what appears to be a BER noise floor at approximately $5x10^{-5}$. Other points tend to approach the theoretical limit of QPSK. In fact, there is no noise floor at this point nor does the modem perform at the QPSK theoretical limit. The false conclusions are primarily due to a lack of understanding of the time-varying nature of the received signal. For these curves there was only one reading for the carrier and noise power, C/N_o. The C/N_o was measured once and not monitored during the BER measurement. The problem is that the signal and noise power is assumed constant for the duration of the BER measurement when, in fact, they are not. It was observed that the signal and/or noise power could change by almost 1 dB during the course of a BER measurement. This is due to the 1 Hz oscillations of the satellite and the thermal distortions of the antenna system. For low E_b/N_o measurements, this is not as noticeable as the BER measurement time is relatively short and the additional errors caused by the oscillating signal are masked in the BER reading. However, for high E_b/N_o, the measurement time increases and the time-varying effects become more noticeable. In these measurements, the oscillating signal power is more prominent due to the few errors recorded. One could observe the effect of the oscillating signal power, by monitoring the BER test equipment and seeing the error counter speed up and slow down, time synchronous with the 1 Hz satellite oscillations.

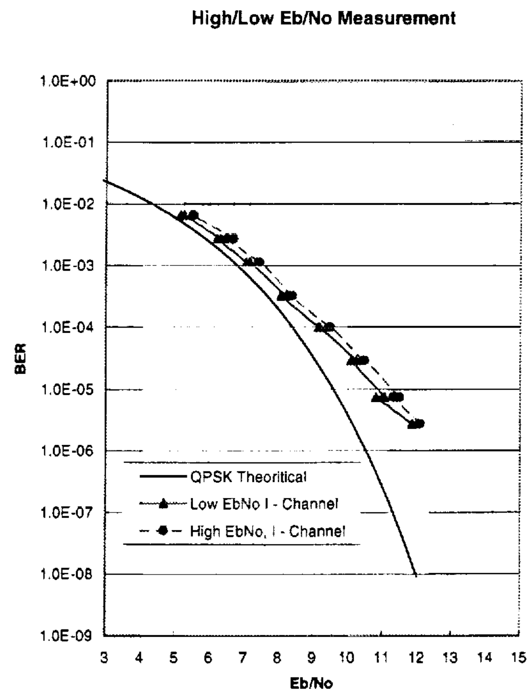

Figure 6 – Minimum and Maximum Eb/No Measurements.

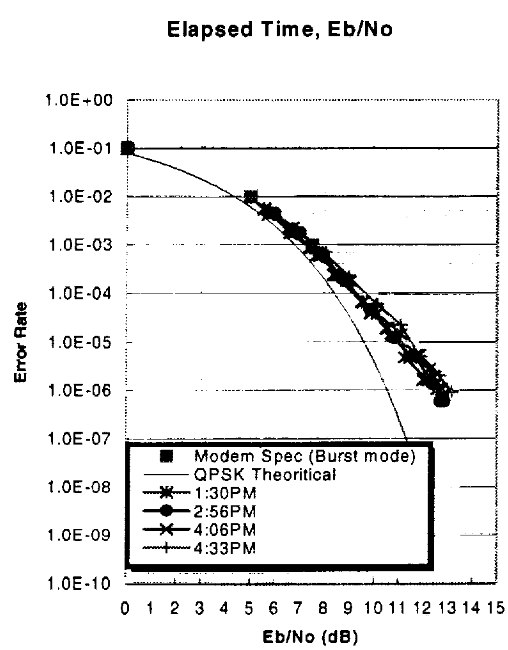

Figure 7 – Avg Eb/No Measurement Results.

Noting the changes in signal and noise power, the measurement technique was modified. For the Noting the changes in signal and noise power, the measurement technique was modified. For the second set of tests the noise power was continuously monitored and recorded. For each measurement, both the high and low noise power and time of day were recorded. The signal level was measured at the beginning and end of each measurement using a continuous tone.

Figure 6 shows two BER curves using QPSK modulation; one assuming the low signal and noise power value and the second assuming the high signal and noise power value. There is approximately a 0.5 dB difference between the two plots.

Figure 7 shows several BER curves (also QPSK) using the average signal and noise density values. The BER curves were recorded for the same modem during different times of the day. This shows that even using the new techniques and taking great care to make accurate measurements the uncertainty is 0.5 dB to 1.0 dB particularly at high E_b/N_o. Taking the average of the high and low signal and noise power (avg C/N_o) or time averaging the signal and noise power density are attempts to characterize an inconstant link. Although the techniques are not exact, they are useful for comparison purpose and yield reasonable results that can be repeated within an acceptable error bound.

The modem described in this report is part of a TDMA/FDMA system for use with the USAT ground stations to demonstrate mesh and star network connectivity and bandwidth-on-demand applications. Although the characterization of the modems was conducted using continuous operation, the modems were designed for burst operation in a TDMA network. Initial characterization of the modem in burst mode operation has begun using the same techniques described here, with results in agreement with the continuous operation mode.

Summary

As a wide Ka-band hard limiting satellite channel, the ACTS offers challenges to testing ground station components and satellite modems. Thermal distortions and mechanical oscillations of the spacecraft multi-beam antenna affected measurement results over short periods of time. A complete understanding of the communication channel characteristics was imperative to obtain meaningful signal and noise power measurements.

This paper describes three methods to measure the signal and noise power in a hard limited channel and summarizes the results of a modem characterization experiment through the ACTS satellite. The measurement techniques can be used to accurately characterize the modem bit error rate performance within acceptable error bounds. Even with care, E_b/N_o results exhibited error bounds up to ± .75 dB due to the time-varying nature of the communication channel.

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13. ABSTRACT ***(Maximum 200 words)***

NASA is using a commercial customized TDMA/FDMA bandwidth on demand modem for use with the Advanced Communications Technology Satellite (ACTS) to highlight the numerous services and experiments that can be performed using small Ka-Band terminals. Characterizing the modems proved challenging due to the characteristics of the satellite transponder. The ACTS channel is hard-limited and up to 900 MHz wide. The channel has some unusual dynamic properties due to the satellite and antenna system, which make modem testing through the satellite challenging and the test requirements stringent. The satellite Multi-Beam Antenna (MBA) has a 1 hertz oscillation induced by the momentum wheel, which causes the transmit antenna pattern to move slightly. This results in a 1 hertz oscillation in the ground station receive power, with amplitude changes up to 1 dB depending on terminal location within a spot beam and associated gain slope. In addition, ACTS experiences a solar induced "thermal event" each day. This "thermal event" occurs when the sun heats the antenna support structure causing the transmit and receive reflectors to mispoint. This results in a slowly decreasing or increasing power density at the ground station receiver as the antenna pattern moves off bore-site. This paper describes the method used to fully characterize the TDMA/FDMA modem through the ACTS wideband, hard-limited transponder. In particular, techniques are discussed for conducting RF measurements on such a channel, the affect that the thermal characteristics and 1 hertz variations have on the accuracy of the results, and suggested means to minimize the error and provide useful and valuable data.

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